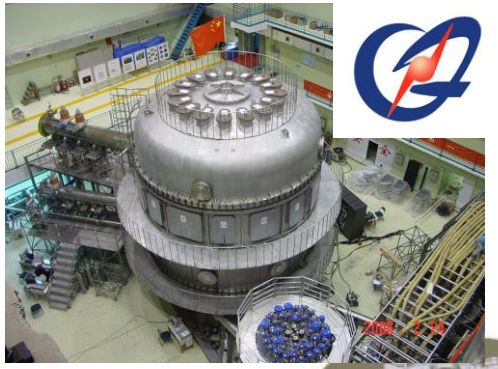
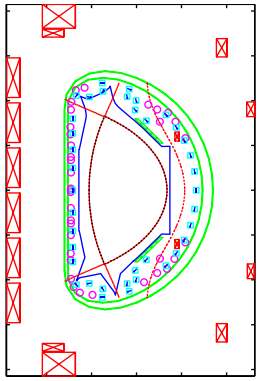
Overview of International Collaboration on "Control and Extension of ITER and Advanced Scenarios to Long Pulse in EAST and KSTAR"

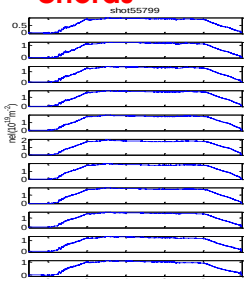
P. Bonoli, D. Humphreys, D. Brower, E. Doyle, A. Garofalo, K. Gentle, C. Holcomb, J-M. Park, W. Rowan, E. Schuster, W. Solomon, US Scenarios/Control Team, ASIPP/EAST Team, NFRI/KSTAR Team

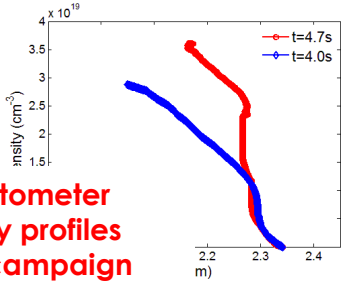


TokSys Model of EAST



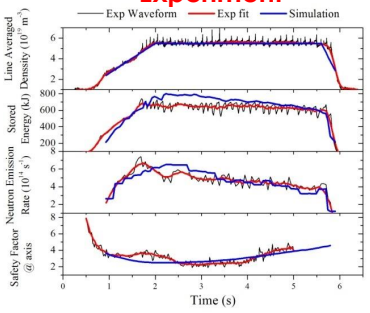
POINT 2015: upgraded from 5 to 11 chords



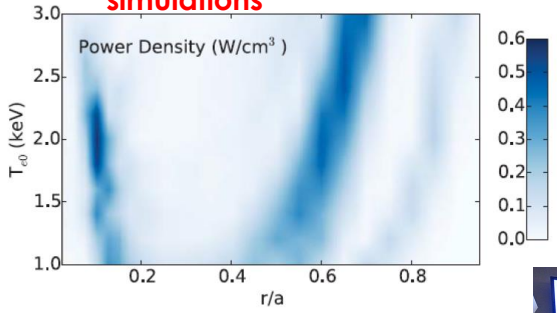


Reflectometer density profiles 2015 campaign

PTRANSP Simulation conducted to reproduce the DIII-D/EAST Joint Experiment



LHCD database for rapid-execution module for control simulations



GA Remote Control Room Supports 3rd Shift Operation of EAST by US Scientists

FESAC Meeting, Bethesda, MD 13-14 January 2016

Outline

- **Overview of Scenarios and Control International Collaboration**
- **Summaries of task elements:**
  - Scenarios task
  - Control task
  - Diagnostics and Actuators task
  - Simulation and Modeling task
  - Remote Collaboration task
- **Selected Lessons Learned to date**
- **Conclusions**

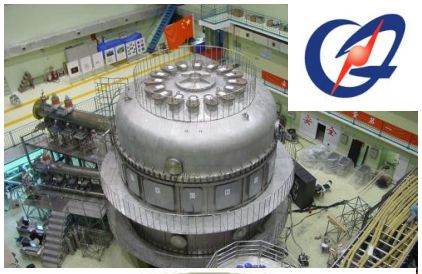
Overview of Scenarios and Control International Collaboration

Scenarios and Control International Collaboration Includes Many Institutions from Across the US Fusion Program

- **US Team and PI's:**
  - GA (PI's: D. Humphreys/A. Garofalo)
  - MIT (PI: P. Bonoli)
  - PPPL (PI: W. Solomon)
  - Lehigh U. (PI: E. Schuster)
  - LLNL (PI: C. Holcomb)
  - ORNL (PI: J-M. Park)
  - UCLA (PI's: E. Doyle/D. Brower)
  - U. Texas (PI's: K. Gentle/W. Rowan)

- **International Collaboration Teams:**
  - ASIPP/EAST: GA/MIT/PPPL/Lehigh/LLNL/UCLA/UT
  - NFRI/KSTAR: GA/MIT/PPPL/ORNL

- **Project Scope:**
  - Long pulse scenarios/control physics studies on EAST and KSTAR
  - Period of Execution: Summer 2013 – Summer 2016



Scenarios/Control Project Consists of Five Closely-Interacting Research Areas

- **Scenarios Task:** (Principals: PPPL, LLNL, GA, MIT, ORNL)
  - Develop understanding of scenario physics in long pulse SC devices
  - Extend experimental scenarios from US devices to EAST and KSTAR: advanced, high performance and ITER fiducial

- **Control Task:** (Principals: GA, MIT, PPPL, Lehigh, LLNL)
  - Advance control science needed for long pulse in superconducting devices
  - Demonstrate and quantify solutions experimentally on EAST and KSTAR

- **Diagnostics/Actuators Task:** (Principals: UCLA, UT, MIT)
  - Implement diagnostics and improve actuator physics understanding
  - Enable new measurements and actuator use for scenarios and control studies in long pulse devices

- **Simulations and Modeling Task:** (Principals: PPPL, ORNL, GA, MIT, LLNL, Lehigh)
  - Perform simulations for scenario development and modeling for control science and design

- **Remote Collaboration Task:** (Principals: GA, MIT, PPPL, LLNL)
  - Develop tools and methods to maximize effectiveness of remote collaboration and experimental participation

Scenarios/Control Project Consists of Five Closely-Interacting Research Areas

- **Scenarios Task:** (Principals: PPPL, LLNL, GA, MIT, ORNL)
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  - Extend experimental scenarios from US devices to EAST and KSTAR: advanced, high performance
- **Control Task**
  - Advance
  - Demonst
- **Diagnostics**
  - Impleme
  - Enable n devices
- **Simulations**
  - Perform
- **Remote Collaboration Task:** (Principals: GA, MIT, PPPL, LLNL)
  - Develop tools and methods to maximize effectiveness of remote collaboration and experimental participation

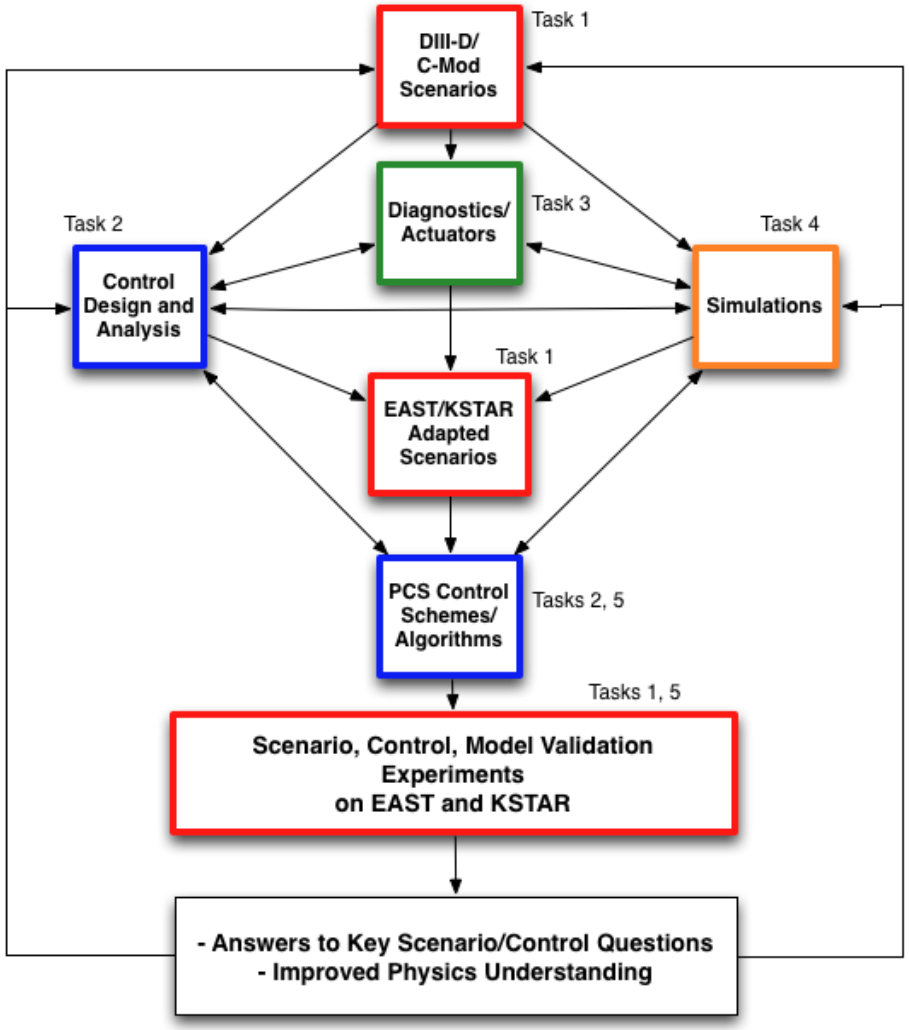
Diversity of subtasks in project structure provides mitigation of uncertainties in machine availability or performance:

➔Progress can still be made if experimental time or plasma performance are limited…

➔Interacting tasks can adapt flexibly to varying machine conditions or experimental program constraints…

Scenarios/Control Collaboration Is Highly-Integrated

- **5 subtasks interact closely:**
  - **Task 1**: Scenarios
  - **Task 2**: Control
  - **Task 3**: Diagnostics/Actuators
  - **Task 4**: Simulations
  - **Task 5**: Remote Collaboration
- **Example institution research links**
  - MIT/GA/Lehigh/LLNL: RF modules in control & scenario simulations; validation in experiment
  - PPPL/ORNL/GA/LLNL/Lehigh: Multiple cross-cutting simulations develop scenarios/control
  - UCLA/UT/GA/PPPL: diagnostics in PCS for critical RT control
  - ALL: coordinated experimental participation on-site…

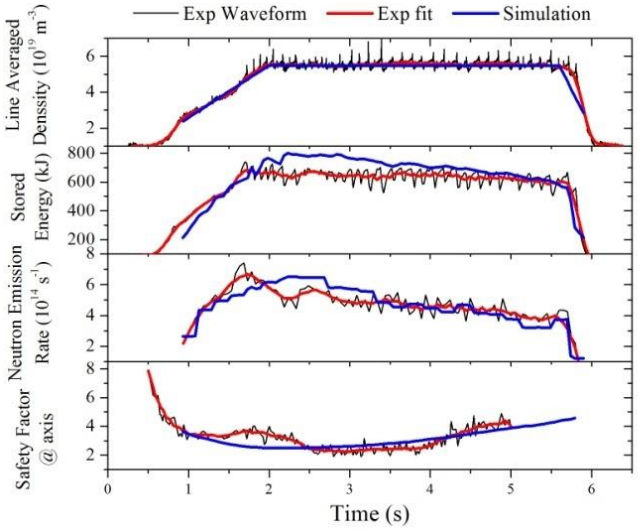


Scenarios
Task Summary

Scenario Understanding Has Been Advanced Through Simulation and Analysis of DIII-D and EAST Experiments

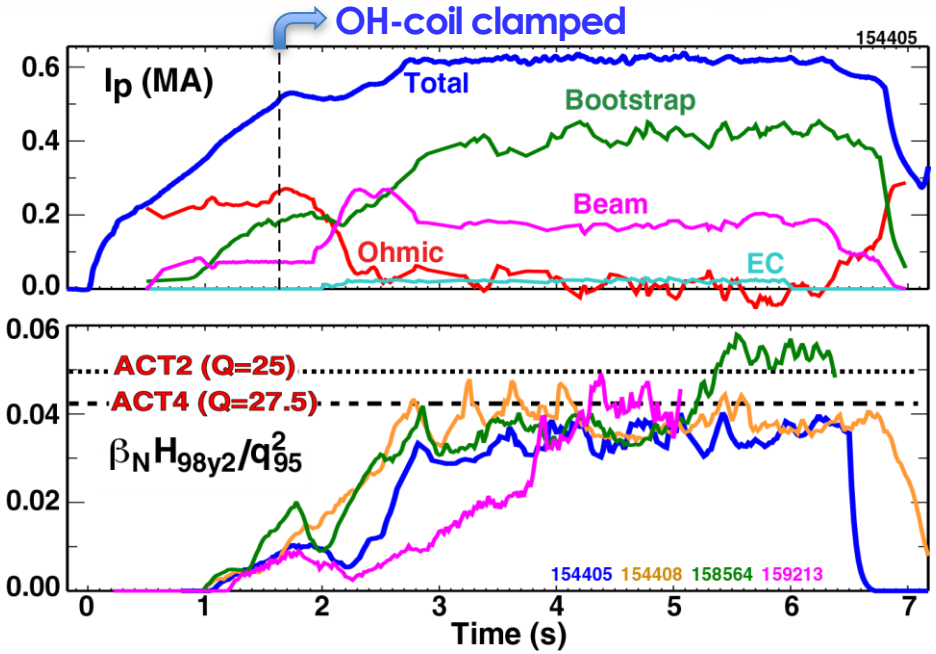
- **Joint experiments on DIII-D developed fully non-inductive high-betap scenario under EAST-relevant conditions**
- **PTRANSP simulations reproduce high betap discharges on DIII-D, predict requirements for scenario on EAST**
- **Annual EAST/DIII-D Joint Planning Workshops enable coordination between programs**
  - 2nd EAST/DIII-D Joint Planning Workshop held at General Atomics, April 6-9, 2015
- **Participation in EAST campaigns has included experiments toward development of high betap long pulse and I-mode scenarios**

PTRANSP Simulation conducted to reproduce the DIII-D/EAST Joint Experiment



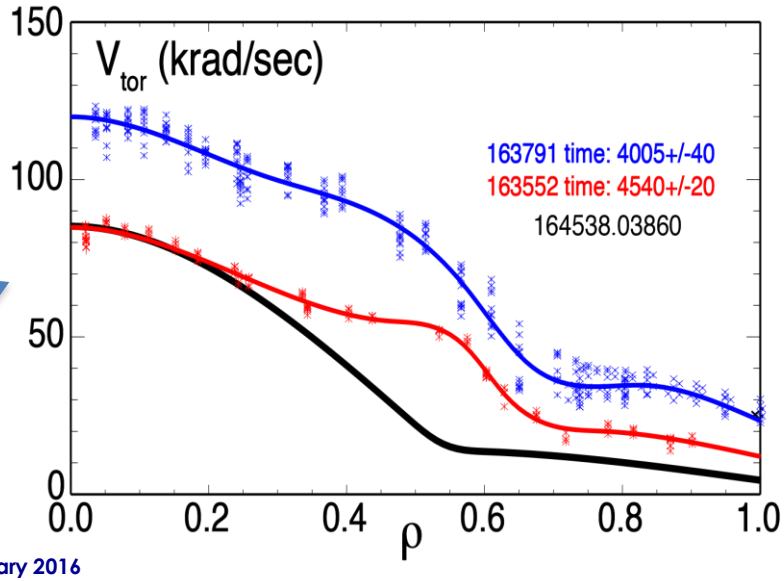
Participants from China and US at EAST/DIII-D Joint Planning Workshop at General Atomics

Joint EAST/DIII-D Experiments on DIII-D Developed a Fully Non-inductive Scenario with Reactor-relevant Performance Under EAST-relevant Conditions (PROVIDED FOR CONTEXT: NOT UNDER GRANT FUNDING…)



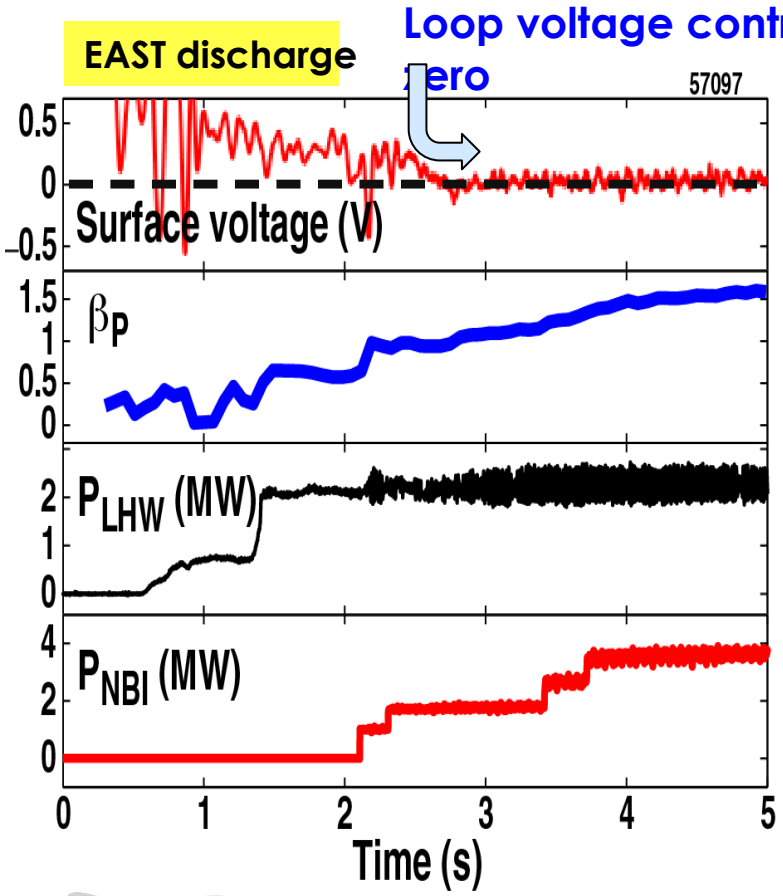
- I_P ramp rate consistent with EAST (~0.2MA/s)
- I_P, B_T, P_{inj} consistent with upgraded EAST capabilities
- ITB at large minor radius for excellent confinement
- Normalized fusion performance comparable to ARIES ACT2 and ACT4 DEMO design studies

- Results presented in invited talk at APS 2015 by Qilong Ren
- Latest DIII-D experiments (December 2015) show robustness of large-radius ITB vs. rotation and q95
  - 164538: Very high confinement (H_{98y2}≤1.8) maintained with strongly reduced rotation



Extension of the DIII-D High Bootstrap Scenario to Long Pulse on EAST Has Begun

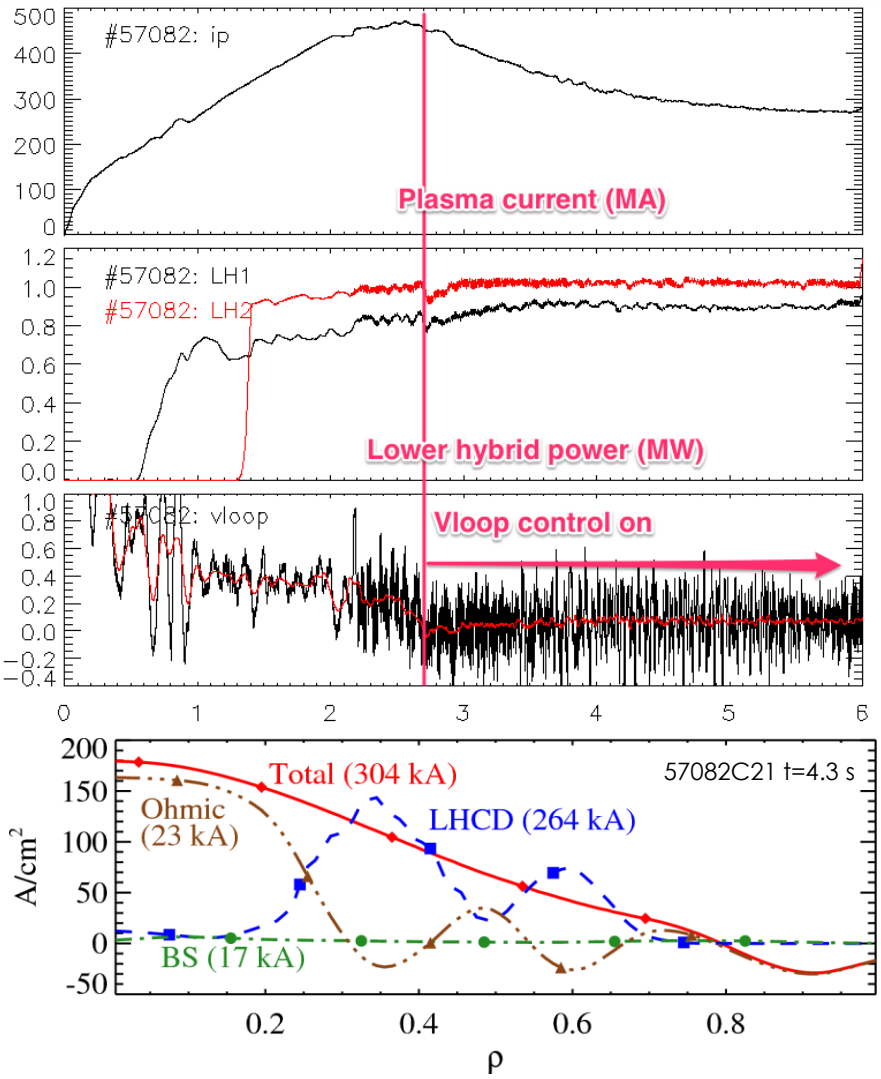
- Loop Voltage Control algorithm successfully developed and deployed on EAST plasma control system



- Discharges terminated by impurity influxes
- Limited in the available power
- Upcoming experiments in 2016 (starting in January) will take advantage of improved wall conditions and at least double H&CD power
  - 6 →12 MW

Heating and Current Drive Analysis Being Performed for Recent EAST Experiments

- **Two days of experiments conducted in July together with GA and LLNL collaborators to develop steady-state plasmas**
- **Used newly developed vloop controller to drive loop voltage to zero and let current evolve based on non-inductive sources**
  - Even with vloop=0, TRANSP finds profiles are far from steady-state
- **TRANSP simulations underway to simulate current evolution and predict fully relaxed solution**



Extension of the I-Mode Scenario to EAST

- **A. Hubbard & S. Wolfe (MIT) and X. Gao, T. Zhang, Z. X. Liu, G. Q. Li, Y. Yang, D.F. Kong, X. Han, & C. Huang (EAST).**
- **EAST / KSTAR are opportunities to extend the range for I-Mode exploration from B_0 ~ 5.4-7.9T to lower field (~ 2T), long pulse discharges.**
- **Have successfully simulated I-mode experiments under EAST conditions on Alcator C-Mod [B_t = 2.75T, I_P = 500 kA, n_e = (5-6) × 10^{19} m^{-3}] using $2\Omega_{CH}$ ICRF heating.**
- **In July, 2015 conducted initial experiments for the proposal "Development and study of I-Mode on EAST".**
  - **The needed USN configuration was not permitted at that time, but we obtained LSN L-H comparisons**
  - **USN was used in the final week of EAST operation. Discharges are being analyzed to bracket the power range for the P(L-H) transition**
  - **I-Mode experiments are being proposed again for 2016 campaigns**

Increased EAST Collaboration on Operations Topics May Contribute to Enhanced Machine Availability/Productivity

- **Challenges in machine availability impacted experimental collaborations on EAST and KSTAR 2013-15, and have motivated new collaborative focus on operations**

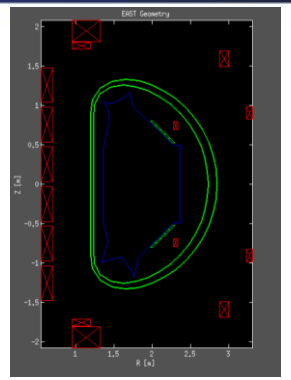
- **Visits to EAST in October 2015 focused on Neutral Beams, Plant Systems, and Operations Collaboration:**
  - Two week visit to ASIPP/EAST by two DIII-D beam scientists (J.T. Scoville, B. Crowley), and DIII-D Tokamak Operations director (A. Kellman)
  - NB focus on ion source conditioning techniques and procedures, identification of opportunities for improvement of EAST beam operational performance
  - General operations focus on major hardware systems, operations procedures, identification of opportunities for operations improvement

- **Future Plans for EAST/DIII-D Neutral Beam and Operations Collaborations:**
  - Operational assistance from DIII-D NB and ECH groups on optimizing performance, reliability, and safety; participation in beam spectroscopy studies…
  - DIII-D support on current operations challenges: divertor performance, Li removal, graphite tile analysis and potential exchange
  - Joint work on divertor development (~2-year time frame)
  - Collaborative development of negative ion source

Control
Task Summary

Control Research Task Studies EAST Controllability and Develops Algorithms to Support Scenario Goals

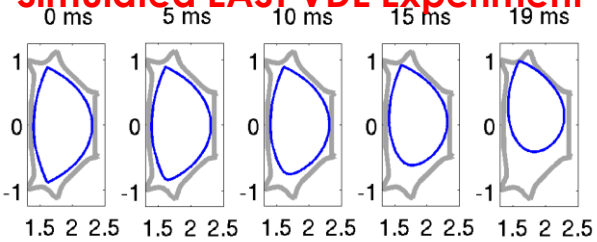
- **EAST model/simulation development for control analysis:**
  - Updated EAST conductor/structure models
  - Validation experiments
  - Control simulation development with new H/CD modules



Updated EAST system model 2015

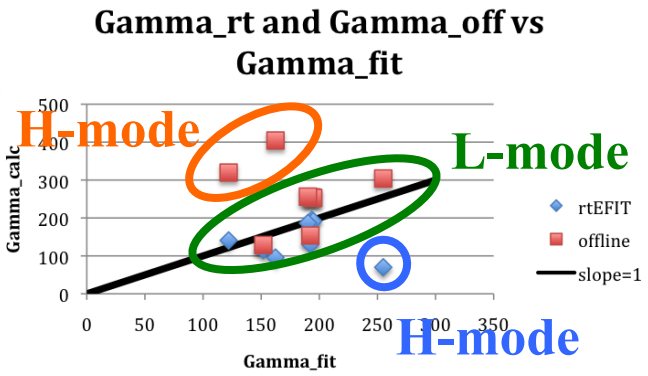
- **Specialized control algorithms for scenarios:**
  - Vertical control optimization
  - Off-normal/fault response algorithms to prevent VDE
  - Loop voltage control for non-inductive scenarios

Simulated EAST VDE Experiment



- **Control research and novel configuration studies:**
  - ITPA MHD joint experiment controllability research: experiment done during EAST 3rd shift
  - Disruption simulation, RE mitigation and control
  - Development of disruption-free rampdown control

Experimental growth rates agree with model for L-mode but not for H-mode

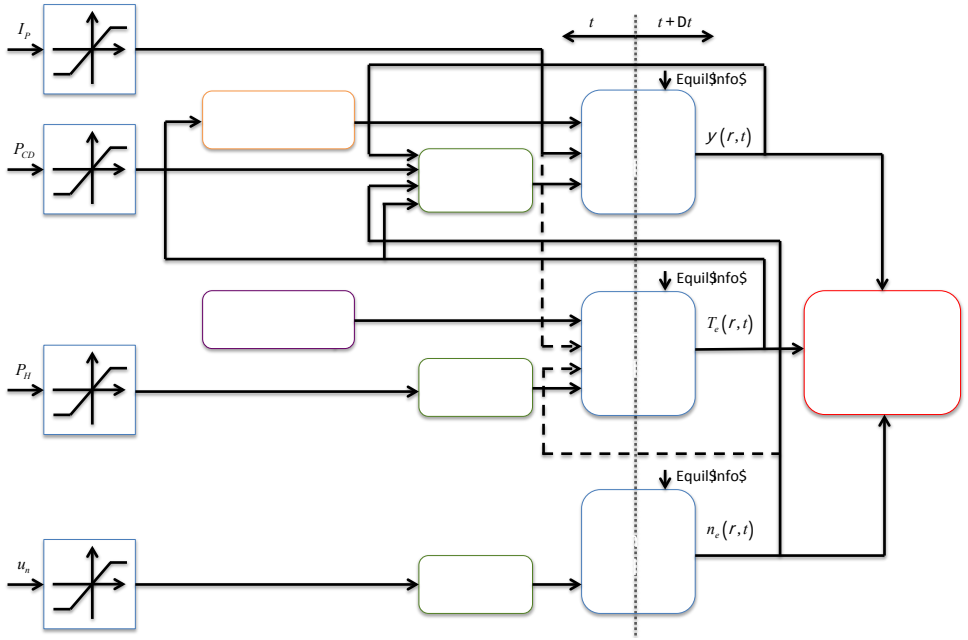


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

Control-oriented Transport Model for Current-profile Control Design (Fast Simulation and Model-based Synthesis) in EAST

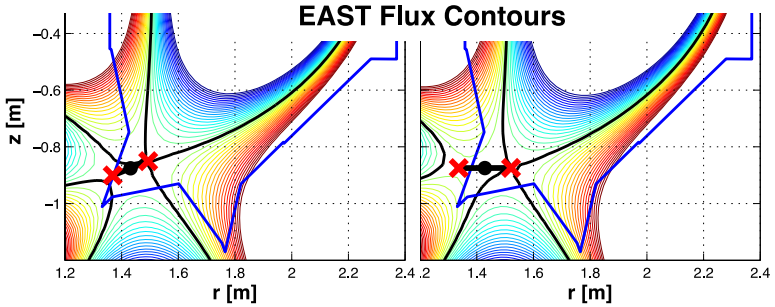
- **Control-oriented Transport Code for Fast Plasma-Profile Prediction in EAST**
  - EAST's magnetic geometry integrated in magnetic diffusion equation (MDE) solver
  - NB and LH H&CD models tailored to TRANSP simulations
  - Integration of MIT's LH current drive & heating source models
  - Development of heat transport equation solver

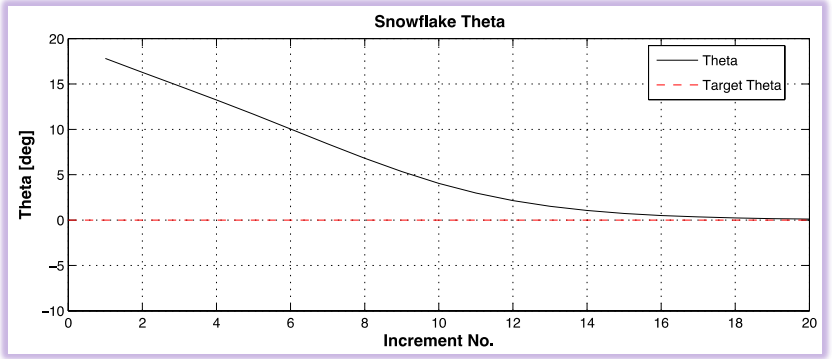


- **Optimization Codes for Systematic Scenario Planning**
  - Nonlinear optimization algorithm coupled with control-oriented transport code
  - Systematic model-based approach to scenario planning in EAST
- **Model-based Feedback Control Design for Current Profile Regulation**
  - Model Predictive Control (MPC) approach enables real-time optimization
  - Observer exploits model to filter measurement "noise" not consistent with physics

Snowflake Divertor (SFD) Control Algorithm Installed and Tested on the EAST Plasma Control System

- **Feedback system uses fast real-time snowflake identification algorithm based on local expansion of the Grad-Shafranov equation to locate the two X-points**
  - **Sensitivity of SFD formation on Poloidal Field (PF) coil is calculated**
  - **PF coil currents needed for desired SFD configuration are calculated based on sensitivity**
- **Simulation of controller performed**
  - **Initially, angle of the SFD formation (θ) ~20° and control asked to adjust to 0° while keeping separation roughly constant**
  - **Currents at the PF coils that are closest to the divertor region are updated continuously to achieve the final state**



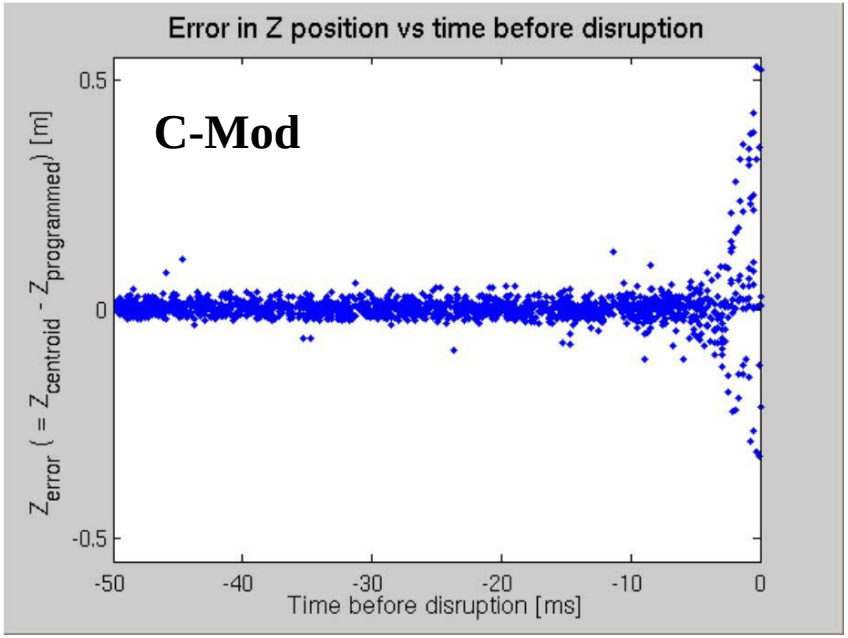


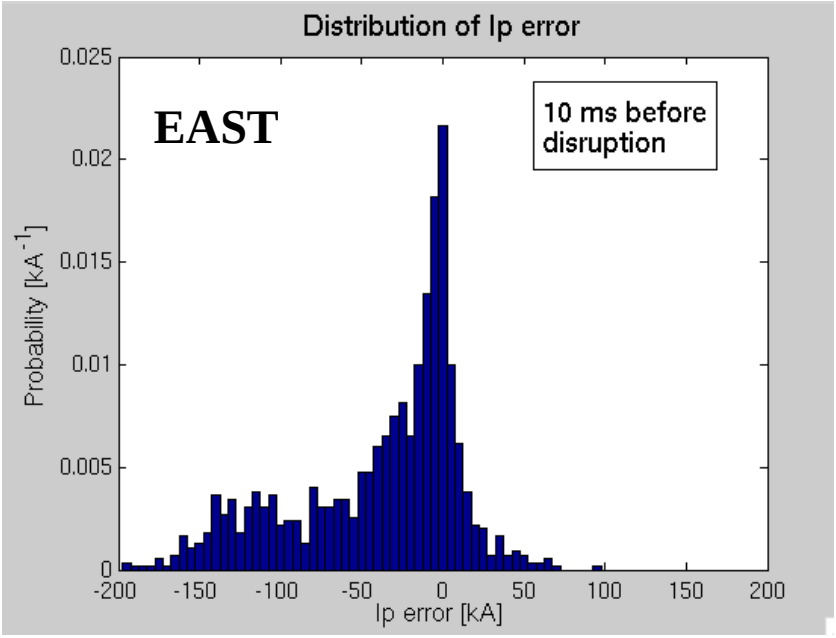
New SFD controller can maintain target geometry, overcoming non-stationarity observed in feedforward implementations

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Control for Long Pulse Disruption-Free Operation in EAST

- **R. Granetz & A. Tinguely (MIT) and Wang Bo (USTC)**
- **Primary activity has been the installment of a disruption database on EAST, which is now fully functional and automatically populated with new disruptions:**
  - **This disruption database was the first SQL database of any kind at EAST.**
  - **Has involved regular visits to EAST by R. Granetz (3 per year).**
- **Developed disruption warning databases for all C-Mod and EAST discharges in 2015:**
  - **Database is modelled after S. Gerhardt NF 53, 063021 (2013).**





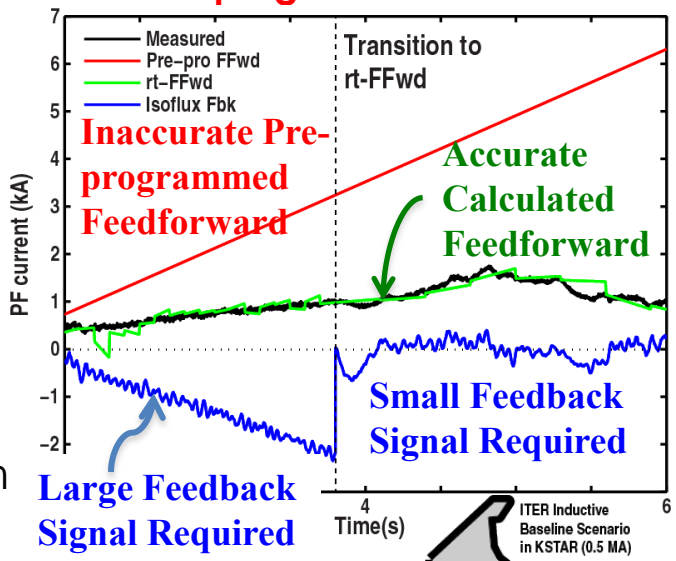
44% of all disruptions have Ip_error ≤ -30 kA

Studies with KSTAR Have Quantified Controllability and Implemented Algorithms to Support Scenario Goals

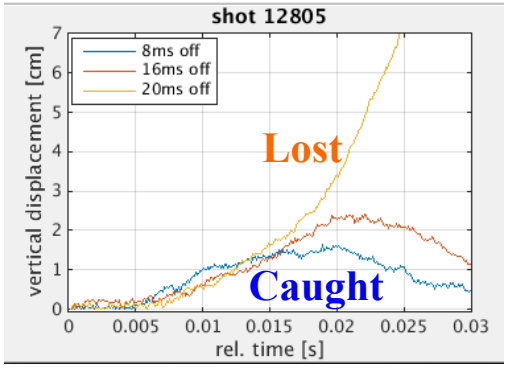
- **Specialized control algorithms developed for ITER Baseline scenario:**
  - New isoflux control scheme for ITER shape
  - Decoupled fast/slow vertical control loops
  - Model-based multivariable shape/x-point control
  - Model-based realtime feedforward coil current trajectory calculation

- **Controllability studies extended:**
  - New "Release and Catch" experiments updated controllability scaling for 2015 passive plate system
  - 2013: ΔZ_{MAX} ~ 1.80 ± 0.80 cm ~ (185 ± 80)/γz
  - 2015: ΔZ_{MAX} ~ 2.47 ± 0.94 cm ~ (274 ± 104)/γz

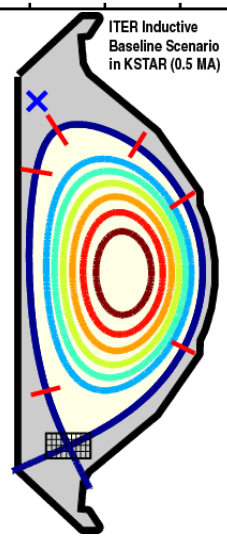
Realtime Feedforward Calculation Removes Large Mismatch Between PF current program and actual



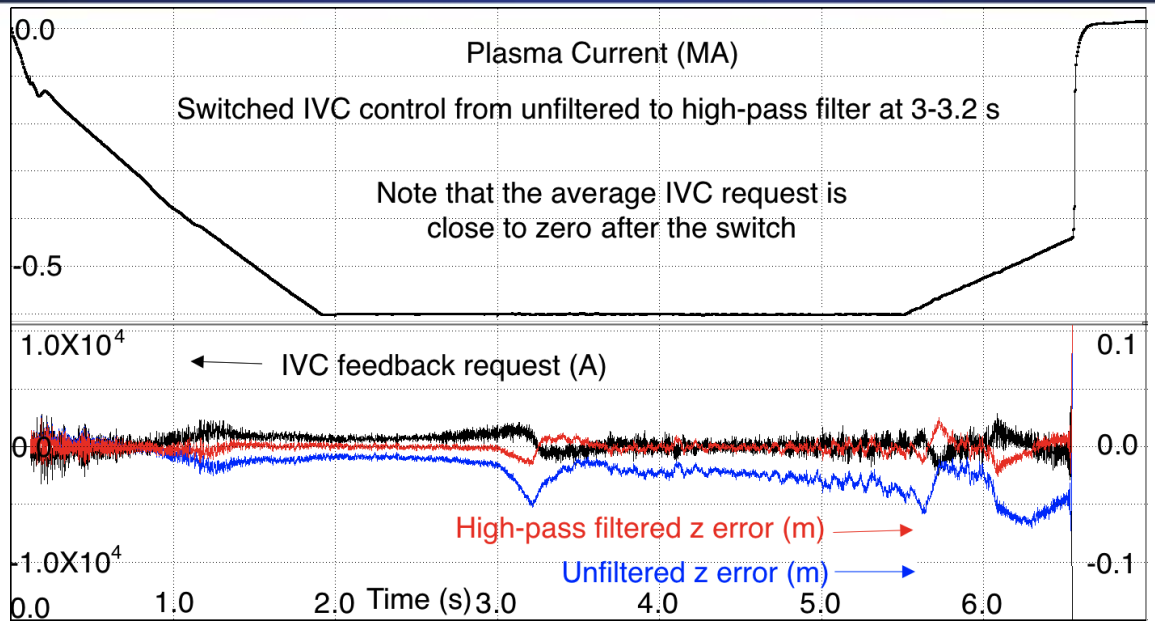
Disabling and Restoring Vertical Control Directly Measures Maximum Controllable Displacement ΔZ_{MAX}



New Isoflux Control Scheme for ITER Baseline in KSTAR



Use Of Filtered Z-error Prevents Loss Of Vertical Control on KSTAR by Keeping IVC Current Near Zero



- **Slow z motion (t~100 ms) due to shape control using superconducting coils can cause the IVC coil to saturate**
  - Lose ability to perform fast control
- **Avoided by employing a high-pass filter (2 Hz) on the fast z error**
- **Use of existing flux loops in fast z estimator limited by passive filtering; improve if instrument flux loops to measure relative flux**

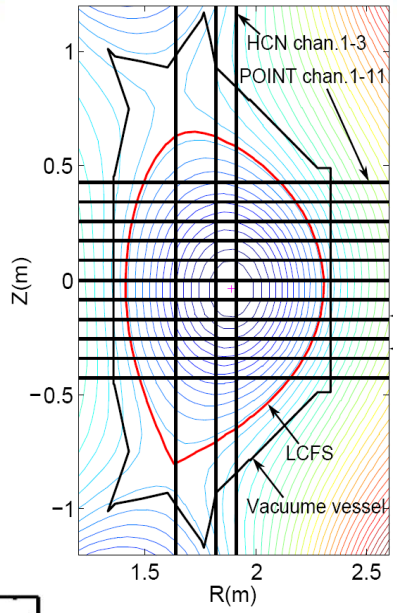
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Improved z-control achieved, aiding in realization of ITER baseline shape. Further improvements possible with new signals

Diagnostics and Actuators
Task Summary

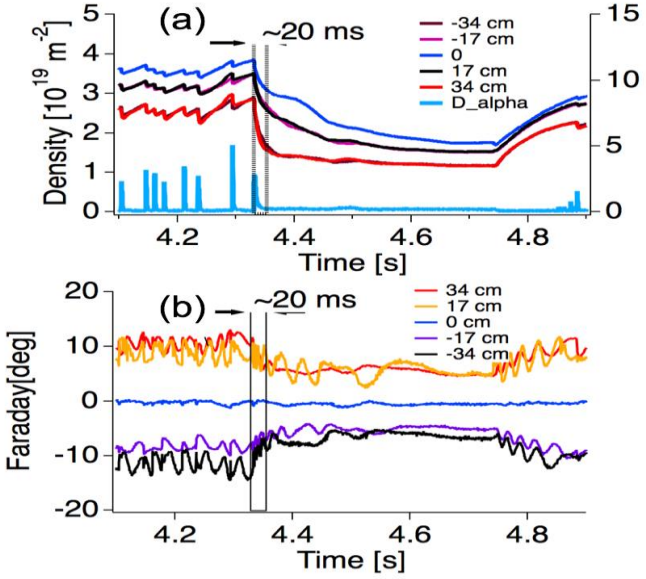
Diagnostic Development on EAST: UCLA Faraday-Effect Polarimetery-Interferometer Diagnostic

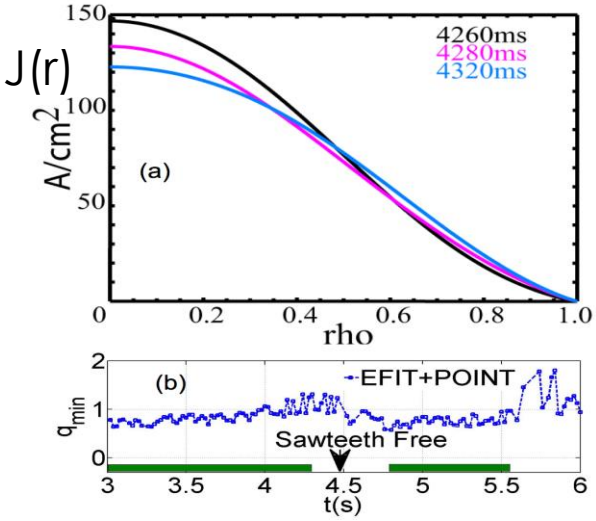
- ***POINT***: ***PO***larimeter-***INT***erferometer system
  - time resolved J(r) and ne(r) profiles throughout discharge for all EAST operation scenarios
  - 2015: upgraded from 5 to 11 chords
  - 2016: polarimeter calibration optimization
  - 2016: provide constraints for EFIT and integrate realtime current density profile data into PCS



11 chord: horizontal view

Fast profile changes at L-H transition

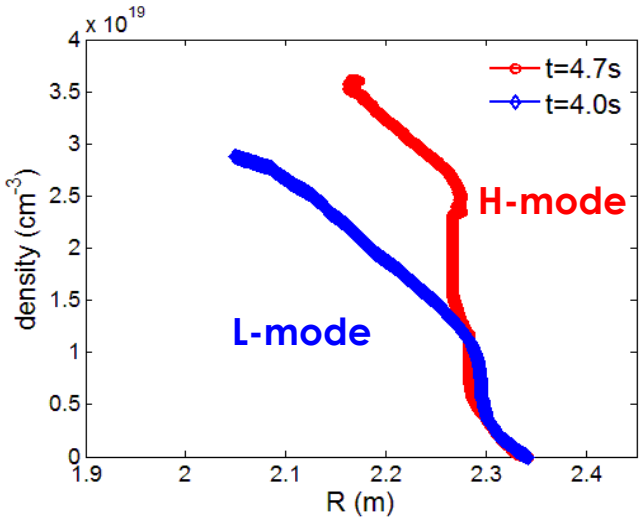


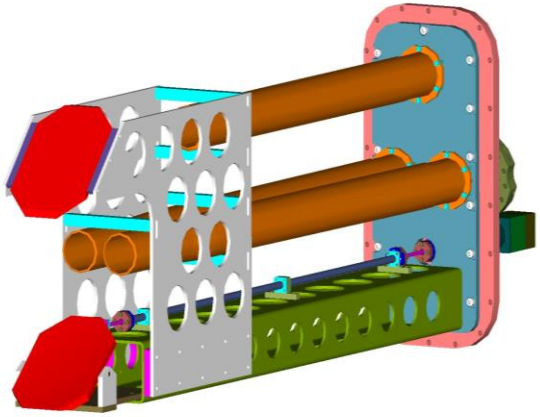


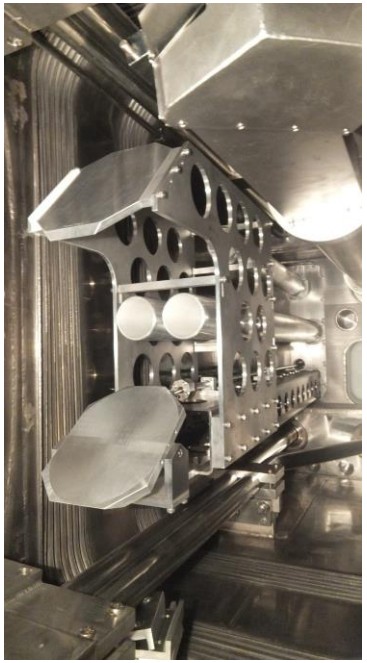
POINT provides realtime measure of current and q profile evolution during long-pulse, high-performance EAST plasma operation

Diagnostic Development on EAST: UCLA-USTC Microwave Reflectometer

- **Profile reflectometer covers 33-75 GHz, with density range of ~0-6.5x10^{19} m^{-3}**
  - Also 50-75 GHz 8-channel Doppler backscattering (DBS) system for turbulence studies
- **System is collaboration between the University of Science and Technology of China (USTC) and UCLA**
  - China funded hardware and construction
  - UCLA designed, constructed and tested new microwave front-end, and provided 8-channel source/receiver system for DBS
- **New microwave front-end installed on EAST in May 2014**
- **New US-supplied microwave transmission line, source/receiver electronics installed on EAST over summer/fall 2014**
- **System commissioning and plasma data in 2015 – first profiles**

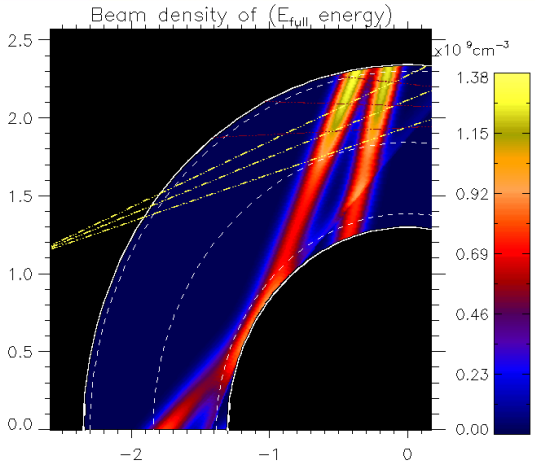




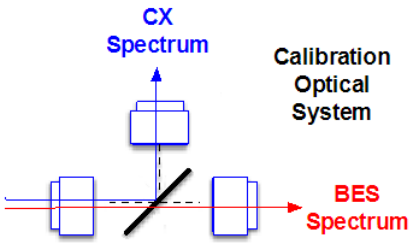


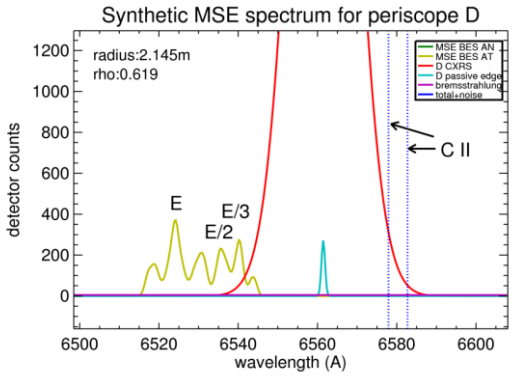
Diagnostic Development on EAST: UT CXRS

- **Providing neutral beam modeling for CXRS and MSE using the ALCBEAM code**
  - Used for diagnostic design
- **Optical system developed for CXRS calibration**
  - Accept light from one plasma chord
  - Split into CXRS spectrum and BES spectrum
  - Send to appropropriate spectrometer for analysis
- **Spin off: spectral MSE measurements are alternate application of spectrum used for CX calibration**
  - UT team providing analysis and xp design
- **EAST MSE synthetic diagnostic developed**
  - Uses fully 3D model of beam and view geometry
  - Spectral MSE performance analyzed
  - Applications to polarization MSE filter design
- **Collaboration-Exchange**
  - ASIPP scientist will visit to acquaint with synthetic diagnostic and C-Mod spectral MSE system
- **ITER JEX9 activity**
  - Experiments to compare spectral MSE and polarization MSE on EAST in 2016



Neutral beam density profiles



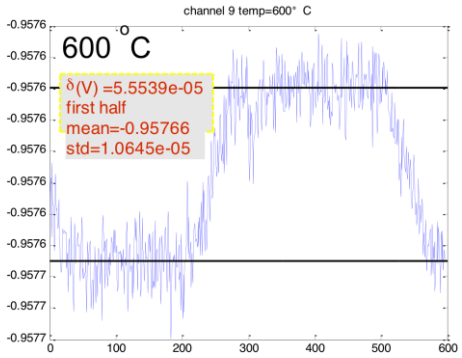


MSE simulation

Diagnostic Development on EAST: ECE

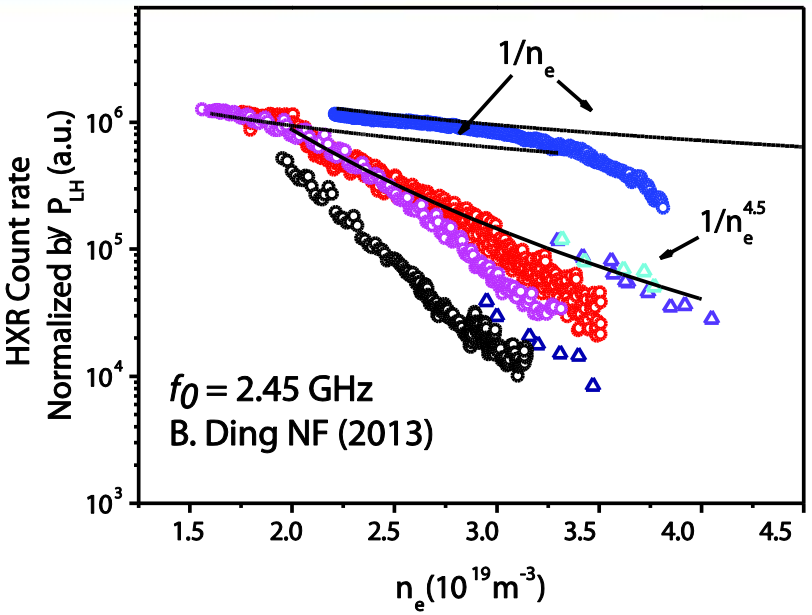
- **Instrument for calibration of ECE**
  - In-situ calibration source for ECE
  - Spin-off from our development of sources for ITER ECE
- **Specially designed in-vessel optics to allow use of calibration source**
  - UT-IFS conceptual design; ASIPP, mechanical design
- **Calibration yields measurement of T_e independent of other diagnostics**
  - Results presented: Chinese Physical Society Fall Meeting
- **PID controller recently developed for automated control of calibration**
- **Active Collaboration**
  - Dr. Liu Yong, Mr. Ang Ti
- **Collaboration Exchange**
  - Postdoc from EAST ECE program will visit for one year to collaborate on common thermal transport experiments
- **On-site at EAST**
  - UT-IFS Engineer, March - June
  - Two UT-IFS Physicists in April

In-Situ Calibration Instrument



Typical Calibration Data

EAST: LHCD Efficiency at 2.45 GHz Decreases Rapidly Above Densities Needed for High Performance Regimes and Physical Mechanisms are Under Study

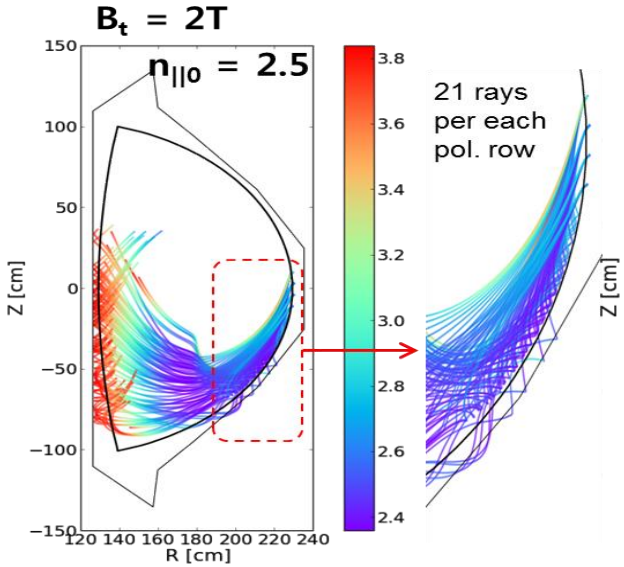


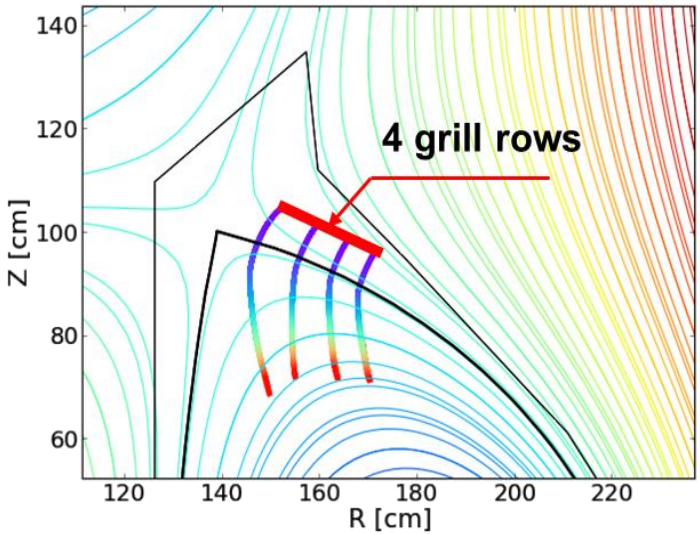
- **P. T. Bonoli, S. Shiraiwa, S. Baek, J. P. Lee, R. Parker, J. C. Wright (MIT) and Bojiang Ding, Miaohui Li, Cheng Yang (EAST).**
- **Availability of both 2.45 GHz and 4.6 GHz LHRF systems on EAST provides a unique opportunity to study the frequency dependence of LHCD as the density is increased.**

- **Ray tracing / Fokker Planck simulations with GENRAY / CQL3D indicate that collisional losses of LH power in the SOL can be significant:**
  - **C. Yang *et al*, PPCF (2014) and B. Ding *et al*., accepted for publication in NF (2015).**
- **LHRF power deposition is sensitive to details in the structure of the coupled wave spectrum:**
  - **S. Shiraiwa *et al*, 21st Topical Conference on RF Power in Plasmas (2015).**
- **Have worked with EAST Team to locate RF probes inside the EAST vacuum vessel to detect PDI spectra and to compute PDI growth rates and decay spectra:**
  - **Indicates significant pump wave depletion at 2.45 GHz in discharges with poor lithiation.**

Analysis of LHRF Actuator for KSTAR Indicates Off-Midplane Launcher Will Provide Improved Access to High Performance H-mode Plasmas Relative to Equatorial Launcher

- **S. Shiraiwa, P. T. Bonoli, J. C. Wright, R. Parker, and G. Wallace (MIT) and Y. S. Bae (KSTAR)**
- **Detailed analysis carried out for with GENRAY / CQL3D to assess LH wave launch in KSTAR from the top position near the upper X-point:**





- **$n_e(0) = 5 \times 10^{19}$ m-3, $T_e(0) = 5$ keV, $B_t = 2$ T**
- **$f_0 = 5$ GHz, $n_{//} = 2.3 – 2.7$**
- **$\eta_{CD} = 0.12 – 0.18$ (10^{20} A/W/m^2)**

Y.-S. Bae, S. Shiraiwa, P. Bonoli, J. C. Wright, R. Parker *et al*, submitted to PPCF (2015).

Simulation/Modeling
Task Summary

CORSICA Progress:

- Identified ~half dozen EAST discharges from July 2015 with various heating and current that will be used for benchmarking CORSICA
- Fixed boundary EAST simulations started based on modification of functioning ITER cases
- More debugging needed: finding and removing ITER-specific items
- Developed new 64-bit version of CORSICA required for high-resolution equilibria
- Preparations underway for presenting a class on the use of Corsica at EAST, January 2016
  - Lectures and hands-on
  - Tom Casper participating, including lectures on using Corsica for his ITER studies

Development of Control-Level LHRF Model for EAST H/CD Control Design and Analysis

- **S. Shiraiwa, P. T. Bonoli (MIT), M. Walker, D. Humphreys (GA), and E. Schuster (Lehigh)**
- **Established a first of its kind profile database for LHCD in EAST based on 880 ray tracing / Fokker simulations :**
  - **To be used in scenario simulation and control studies by GA (TokSys) and Lehigh.**
  - **GENRAY / CQL3D simulations run on the python-based πScope widget at MIT.**
  - **Simulations scan a parameter space in $T_e(0)$, $n_e(0)$, and I_p, at fixed B_0 and $n_{//}$.**
  - **Will produce a similar database for C-Mod and test against experiment.**

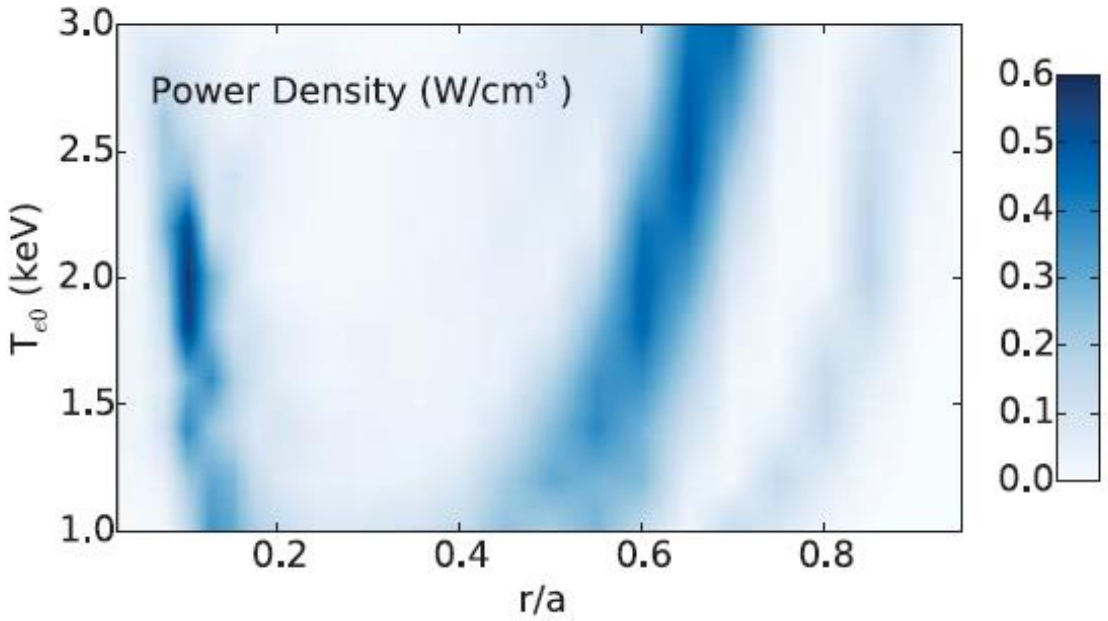
$B_0 = 2.24T$

$f_0 = 2.45$ GHz

$n_{//} = 2.1$

$I_p = 0.48$ MA

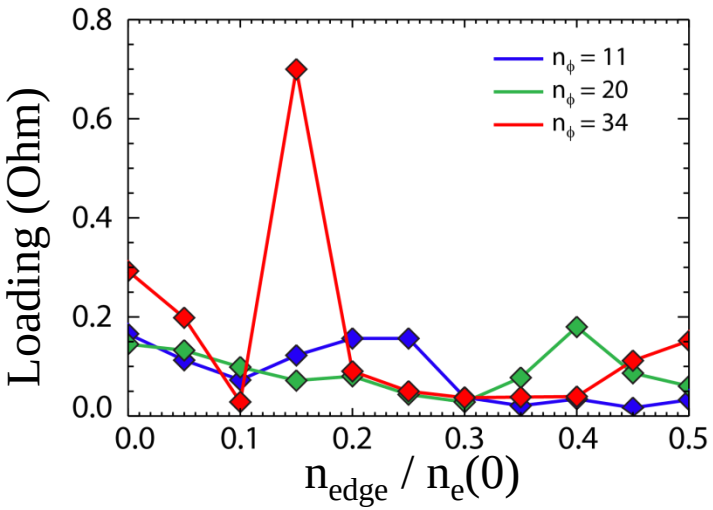
$n_e(0) = 5\times10^{19}m^{-3}$



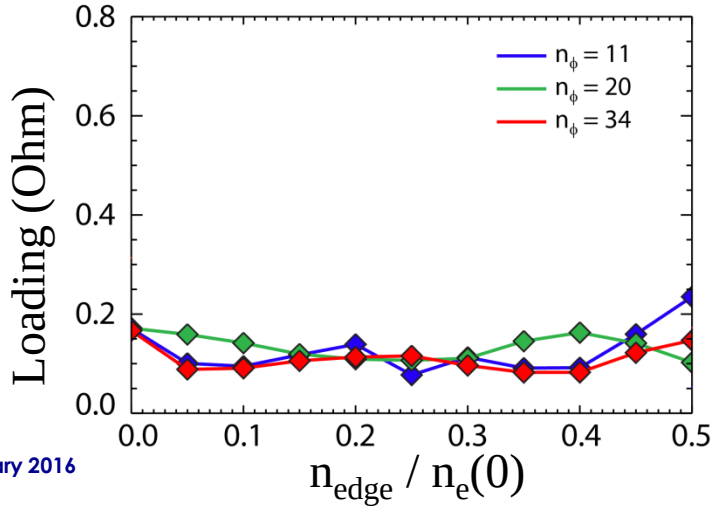
ICRF Actuator Model Development for EAST – crosscutting with Int. Collab. on Development of Long-Pulse RF (Wukitch)

- **E. Edlund, P. T. Bonoli, M. Porkolab, S. Wukitch (MIT) and X. Zhang (EAST)**
- **Original goal: build a control level actuator model from parameter scans in the TORIC solver:**
  - **Total coupled power & profiles**
  - **Scan density, plasma composition, antenna frequency and phasing, SOL width and scale length**
- **Theoretical analysis suggests good single pass absorption for ICRF power.**
- **However, full-wave simulations indicate poor ICRF wave coupling, especially for larger n_ϕ and lower density where the ICRF wave accessibility condition is not well-satisfied:**
  - **Evidenced by eigenmode behavior in loading as density is varied.**
- **Points to a fundamental problem with the original ICRF antenna design → coupled $k_{//} \sim (n_\phi / R)$ is too high.**

$n_e = 0.3 \times 10^{20}$ m^{-3} (typ. EAST)

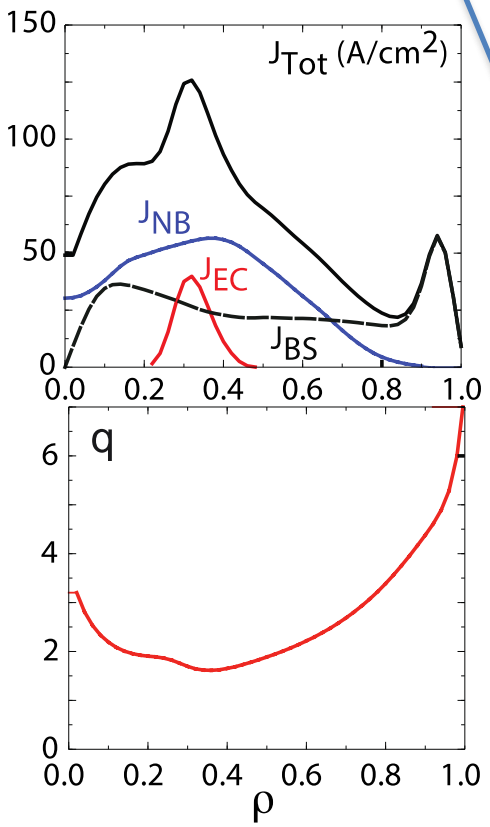


$n_e = 1.2 \times 10^{20}$ m^{-3} (C-Mod like)



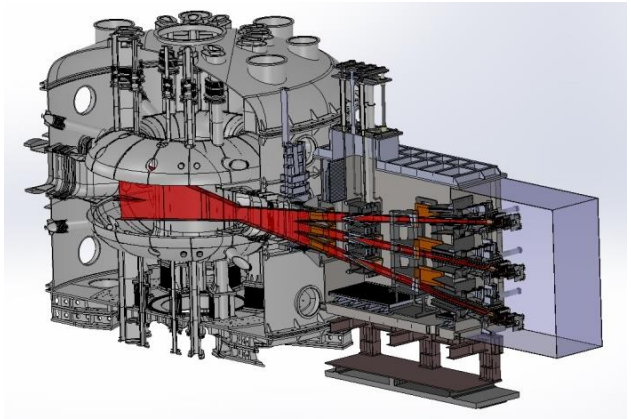
Simulations of Advanced Scenarios Accelerate KSTAR Research Program

- **KSTAR scenario modeling**



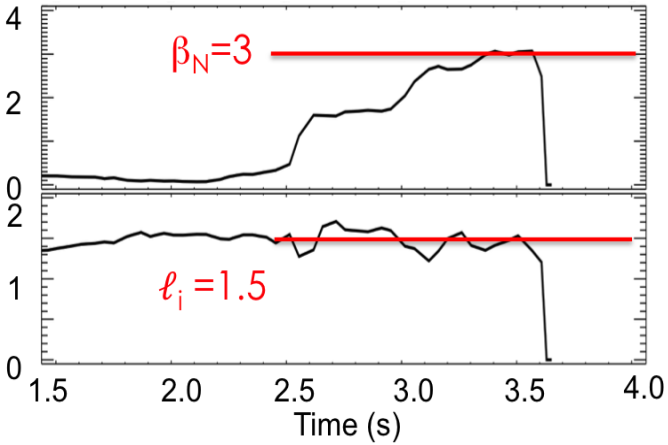
- **Optimize KSTAR H/CD upgrade choice**
  - FASTRAN/IPS predicts off-axis NBCD is crucial to achieving high β Steady State scenario at KSTAR

Preliminary design of KSTAR off-axis NBI



- **Extend DIII-D Steady State scenarios to KSTAR long pulse**
  - Export ***DIII-D high li scenario*** to KSTAR
  - High β_N~3 operation demonstrated at li~1.5, but transiently

2015 KSTAR high li SS discharge



OAK RIDGE National Laboratory

Remote Collaboration
Task Summary

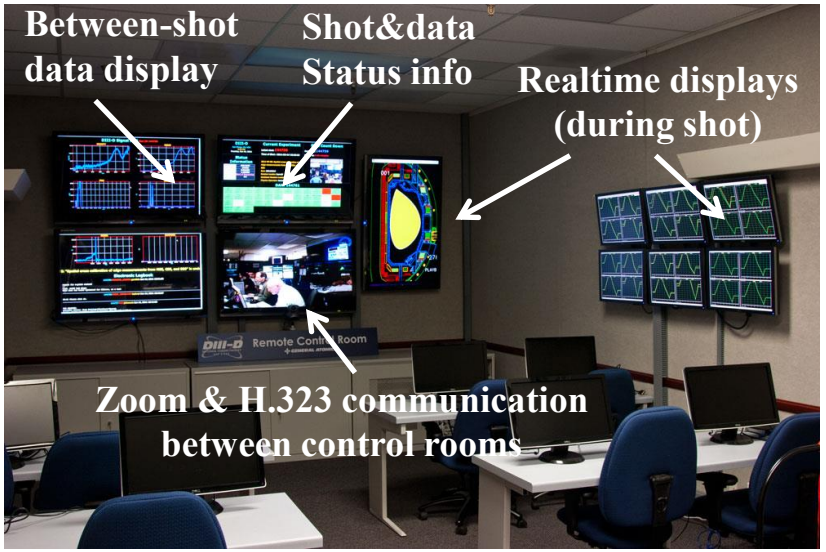
Remote Collaboration Task Implements Communication/Data Access Tools to Enhance US Scientist Effectiveness

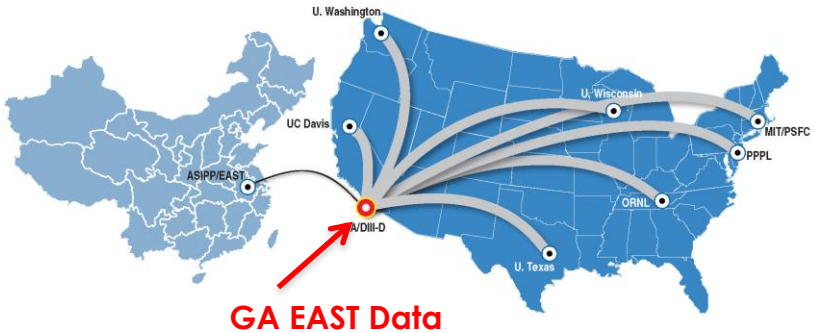
- **GA Remote Control Room:**
  - Display hardware and software to provide control room experience remotely
  - Accommodates 8 scientists and remote communication support staff
  - Audio/video connection to EAST control room, headphone links to key individuals

- **Operations and physics data display resources:**
  - Shot cycle, countdown clock display
  - Realtime in-vessel view video image from EAST
  - Pseudo-realtime signal traces and plasma boundary evolution displayed during shot (~100 ms delay)

- **GA Science Collaboration Zone:**
  - Utilizes 80% of a 1 GB/s network between GA and ASIPP through specialized tools
  - Maximum network utilization allows between-shot transfer of EAST data
  - Data mirror at GA serves all US collaborators

General Atomics Remote Control Room Supports 3rd Shift Operation of EAST by US Scientists





GA EAST Data Repository

GENERAL ATOMICS

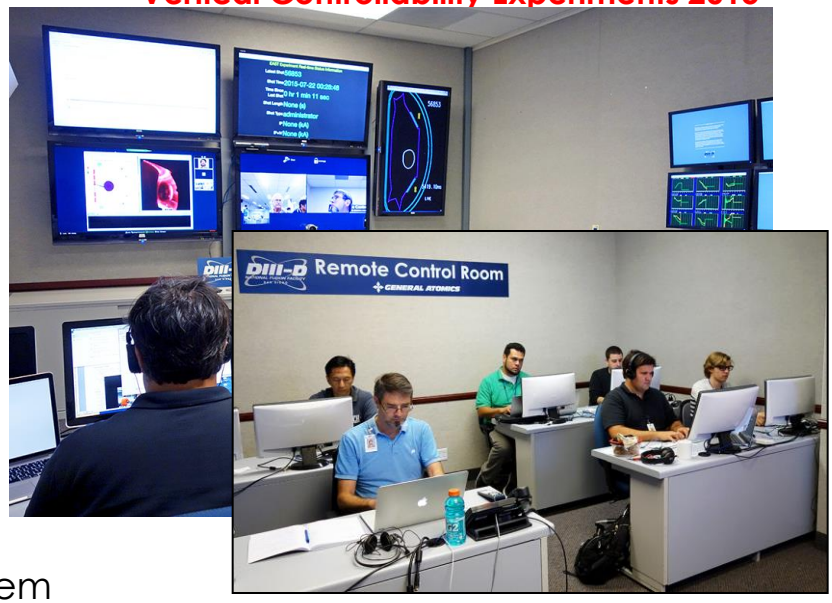
Remote 3rd Shift Experimental Operation Successfully Demonstrated for Two Consecutive EAST Nights in 2015

- **Remote operation is a research activity itself:**
  - Experimenting with approaches to running remote experimental physics sessions…
  - What are performance specs needed for data display infrastructure?
  - How to best communicate and do science?

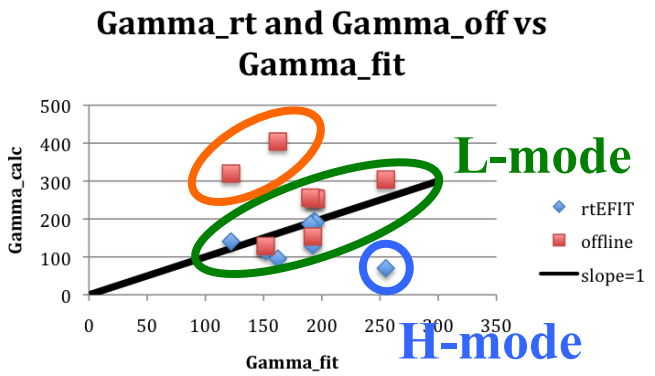
- **Some lessons learned to date:**
  - Higher refresh rate needed in boundary display to correlate with realtime video camera
  - Communication between remote/on-site physics operators(PO) requires sound isolation
  - Remote programming of EAST Plasma Control System with confirmation check by EAST PO is very efficient

- **3rd Shift Vertical Controllability Experiment 2015:**
  - Triggered VDE's to assess vertical growth rate, nonlinear evolution
  - Plasma vertical Release&Catch to directly assess maximum controllable displacement
  - EAST superconducting PF, Cu in-vessel coils provide unique environment for controllability

3rd Shift Operation of EAST by US Scientists for Vertical Controllability Experiments 2015



Experimental growth rates agree with model for L-mode but not for H-mode



Lessons Learned, Scientific Output, and Conclusions

Many Important Lessons Have Been Learned in Scenarios/Control International Collaboration

- **US collaborative role has been highly beneficial to EAST and KSTAR programs, enhancing productivity and providing focused results of specific importance to US**
- **Effectiveness of EAST/KSTAR collaborations depends significantly on sufficient planning and preparation for visits and remote experiments**
- **Machine availability and performance have been challenges for experimental studies on both EAST and KSTAR in the project period 2013-15, however:**
  - Diverse project structure (i.e. beyond experimental participation) enables progress even when machine availability/performance are limited
  - Increased US involvement in operations on EAST may contribute to improved productivity
- **Development of methods and policies for multi-institution, international coordination of data ownership and publication responsibilities have been key to collaboration**
- **Long-term travel to China and Korea remains challenging, but multiple ~2 week visits per year are optimal for most US scientist collaborations on-site at EAST and KSTAR**
  - Diagnostics collaborations have tended to require longer, sustained visits
  - Remote collaboration tools have dramatically increased US impact when scientists are off-site

Rich Scientific Output is Resulting from Collaboration: Publications and Presentations (1)

- A. Garofalo, et al, "Compatibility of internal transport barrier with steady state operation in the high bootstrap fraction regime on DIII-D," Nucl. Fus. **55** (2015) 123025
- B. Wan, et al, "Development of fully non-inductive scenario at high bootstrap fraction for steady state tokamak operation on EAST," 41st EPS Conf. (2014) O2.104
- X. Gong, "Development of fully non-inductive scenario at high bootstrap current fraction for steady state tokamak operation on DIII-D and EAST," IAEA FEC 2014, EX/P2-39
- C. Holcomb, et al, "Fast ion transport in qmin>2 high beta steady state scenarios on DIII-D," Phys. Pl. **22** (2015) 055904
- Q. Ren, et al, "Progress toward steady-state tokamak operation exploiting the high bootstrap current fraction regime," subm. To Phys. Pl. 2015
- E.J. Doyle, A.D. Liu, X. Nguyen, W.A. Peebles, G. Wang, C. Wannberg, and C.X. Yu, "*Design and Testing of an Integrated Microwave Front-end System for Profile Reflectometer and Doppler Backscattering Measurements on EAST.*" Presented at the 20th Topical Conference on High Temperature Plasma Diagnostics (HTPD), Atlanta, GA, June 1-5, 2014
- G. Wang, W.A. Peebles, E.J. Doyle, C. Wannberg, T.L. Rhodes, "*Quasi-optical Coupling into Overmoded Corrugated Waveguide for Reflectometry Applications in Existing and Next-step Fusion Plasmas.*" Presented at the 20th Topical Conference on High Temperature Plasma Diagnostics (HTPD), Atlanta, GA, June 1-5, 2014
- C. Zhou, A.D. Liu, H. Li, J.Q. Hu, M.Y. Wang, X.H. Zhang, C.X. Yu, W.D. Liu, E.J. Doyle, X. Nguyen, W.A. Peebles, G. Wang, "*Preliminary Results from the Eight-channel Doppler Backscattering and Profile Reflectometer Systems on the EAST Tokamak.*" Presented at the 7th US-PRC Magnetic Fusion Collaboration Workshop, Nanjing, China, November 10-12, 2014
- G. Wang, E.J. Doyle, W.A. Peebles, X. Nguyen, and C. Wannberg, A.D. Liu, H. Li, C. Zhou, J.Q. Hu, M.Y. Wang, X.H. Zhang, W.D. Liu, and C.X. Yu, "*Laboratory Testing and First Plasma Measurements with a New, Integrated Profile Reflectometer and Doppler Backscattering System for the EAST tokamak.*" Presented at the 12th International Reflectometry Workshop, Juelich, Germany, May 18-20, 2015
- J.Q. Hu[1], A.D. Liu E.J. Doyle, G. Wang[2], H. Li, C. Zhou, X.H. Zhang, M.Y. Wang, J. Zhang, C.X. Yu, "*Upgrades to the profile and Doppler reflectometer systems on EAST*". Presented at the 57th APS DPP Conference, Savannah, GA, November 16-20, 2015
- C. Zhou, A.D. Liu, M.Y. Wang, J.Q. Hu, J. Zhang, H. Li, X.H. Zhang, T. Lan, J.L. Xie, W.D. Liu, C.X. Yu , E.J. Doyle, "*Turbulence studies using a Doppler Backscattering (DBS) system during ELM mitigation and suppression on EAST*". Presented at the 57th APS DPP Conference, Savannah, GA, November 16-20, 2015
- A.D. Liu, J.Q. Hu, J. Zhang, H. Li, C. Zhou, X.H. Zhang, M.Y. Wang, T. Lan, J.L. Xie, W.D. Liu, C.X. Yu, E.J. Doyle, "*A simple frequency sweep linearization method for FM density profile reflectometry*". Presented at the 57th APS DPP Conference, Savannah, GA, November 16-20, 2015

Rich Scientific Output is Resulting from Collaboration: Publications and Presentations (2)

- Y.-S. Bae, S. Shiraiwa, P. Bonoli, J. C. Wright, R. Parker, J. H. Kim, W. Namkung, M. H. Cho, B. H. Park, S. W. Yoon, Y. K. Oh, H. Park, "Simulation Study of Off-Midplane LHCD in KSTAR," subm. to Plasma Physics and Controlled Fusion 2015
- P. T. Bonoli, "Review of recent experimental and modeling progress in the lower hybrid range of frequencies at ITER relevant parameters", Physics of Plasmas 21, 061508 (2014)
- B. Ding, L. Zhang, M. Li, Y. Yang, W. Wei, Y. Li, S.Wang, M. Wang, H. Xu, G. Xu, L. Zhao, H. Hu, H. Jia, M. Cheng, Y. Yang, L. Liu, H. Zhao, Y. Peysson, J. Decker, M. Goniche, L. Amicucci, R. Cesario, A. A. Tuccillo, S. G. Baek, R. R. Parker, P. Bonoli, C. Yang, H. Liu, G. Li, J. Shan, F. Liu, Y. Zhap, X. Gong, L. Hu, X. Gao, H. Guo, B.Wan, and J. Li, "Investigation of LHW-Plasma Coupling and Current Drive Related to H-Mode Experiments in EAST", 25th Fusion Energy Conference (FEC 2014), Saint Petersburg, Russia, 13 -18 October 2014 Conference ID: 46091 (CN-221), Paper EX/P3-11
- B. J. Ding, Y. C. Li, L. Zhang, M. H. Li, W. Wei, E. H. Kong, M. Wang, H. D. Xu1, S.. L. Wang, G. S. Xu, L. M. Zhao, H. C. Hu, H. Jia, M. Cheng, Y. Yang, L. Liu, H. L. Zhao, Y. Peysson, J. Decker, M. Goniche, L. Amicucci, R. Cesario, A. A. Tuccillo, S. G. Baek, R. Parker, P. T. Bonoli, F. Paoletti, C. Yang, J. F. Shan, F. K. Liu, Y. P. Zhao, X. Z. Gong, L. Q. Hu, X. Gao, B. N. Wan, J. G. Li, and the EAST team, "Investigations of LHW-plasma coupling and current drive at high density related to H-mode experiments in EAST", Nuclear Fusion 55 (2015) 093030
- Z. Xing, B. Xiao, Z.P. Luo, M.L. Walker, D.A. Humphreys, "Strikepoint control on EAST using an isoflux control method," Pl. Sci. and Tech. **17** (2015) 774
- E. M. Edlund, P. Bonoli, M. Porkolab, S. J. Wukitch, "Modeling of EAST ICRF Antenna Performance Using the Full-wave Code TORIC", 21st Topical Conference on Radio-frequency Power in Plasmas, 27-29 April 2015, Lake ArrowHead, CA.
- A. Hubbard, T. Osborne, F. Ryter, X. Gao, J. Ko, R. M. Churchill, I. Cziegler, M. E. Fenstermacher, S. Gerhardt, P. Gohil, J. Hughes, Z. Liu, A. Loarte, R. Maingi, L. Barrera Orte, R. Fischer, P. Manz, A. Marinoni, R. McDermott, G. R. McKee, E. Marmar, J. Rice, L. Schmitz, C. Theiler, E. Viezzer, J.Walk, D. Whyte, A. White, S. M.Wolfe, E.Wolfrum, Z. Yan, T. Zhang, and T. Happe, "Multi-Device Studies of Pedestal Physics and Confinement in the I-Mode Regime", 25th IAEA FEC, Saint Petersburg, RF (2014) EX/P6-22
- Y. Peysson, J. Decker, E. Nilsson, J. -F. Artaud, A. Ekedahl, M. Goniche, J. Hillairet, B. Ding, M. Li, P. T. Bonoli, S. Shiraiwa, and M. Madi, "Advances in Modeling of Lower Hybrid Current Drive", accepted for publication in Pl. Physics and Controlled Fusion (2015)
- S. Shiraiwa, S. G. Baek, P. Bonoli, I. Faust, O. Meneghini, R. Mumgaard, R. Parker, G. Wallace, S. Scott, R. W. Harvey, B. J. Ding, M. H. Li, and C. Yang, "Impact of edge plasma on Lower Hybrid Current Drive: Experimental evidence, mitigation and modeling approaches", 21st Topical Conference on Radio-frequency Power in Plasmas, 27-29 April 2015, Lake Arrow Head, CA
- C. Yang, P. T. Bonoli, J. C. Wright, B. J. Ding, R. Parker, S. Shiraiwa, and M. H. Li, "Modelling of the EAST lower-hybrid current drive experiment using GENRAY/CQL3D and TORLH/CQL3D", Plasma Physics and Controlled Fusion **56**, 125003 (2014)
- S.H. Hahn, Y.M. Jeon, H. Han, H.S. Ahn, J. Kim, Y.J. Kim, M. Youngh, M.H. Woo, D. Mueller, N.W. Eidietis, M. Lanctot, D.A. Humphreys, A.W. Hyatt, A.S. Welander, M.L. Walker, E. Kolemen, Y.S. Park, S.A. Sabbagh, "Enhancement of KSTAR Plasma Control for Expanding Operational Space," 57th Annual Mtg. of the APS Div. of Pl. Phys., Savannah, GA (2015) PO6.12

Rich Scientific Output is Resulting from Collaboration: Publications and Presentations (3)

- Q. Ren et al, "Test of bootstrap current models using high-βp EAST-demonstration plasmas on DIII-D", Plasma Phys. Control. Fusion **57** 025020 (2015)
- V. Budny et al, "TRANSP predictive modeling of EAST steady state plasmas", 56th Annual Meeting of the APS Division of Plasma Physics, New Orleans, Louisiana (2015)
- D. Mueller et al. "Improvements in the fast vertical control systems in KSTAR, EAST, NSTX and NSTX-U", PPC/P8-17, IAEA (2014)
- L. Liu et al, "Improved sensing of vertical velocity for vertical position control using loop voltage signals on EAST", submitted to Plasma Science and Technology (2015)
- H. Q. Liu, Y.X. Jie, W.X. Ding, D.L. Brower, Z.Y. Zou, W.M.Li, Z.X. Wang, J.P. Qian, Y. Yang, L. Zeng, T. Lan, X.C. Wei, G.S.Li, L.Q. Hu, and B.N. Wan, *Faraday-Effect Polarimeter-Interferometer System for current density measurement on EAST*, Rev. of Sci. Instr. **85**, 11D405 (2014)
- Y. Yang, G. S. Li, H.Q. Liu, Y.X. Jie, W.X. Ding, D.L. Brower, X. Zhu, Z.X. Wang, L. Zeng, Z.Y. Zou, X.C. Wei, and T. Lan, *Design of vibration compensation interferometer for EAST tokamak*, Rev. of Sci. Instr. **85**, 11D404 (2014)
- Z.Y. Zou, H.Q. Liu, Y.X. Jie, W.X. Ding, D.L. Brower, Z.X. Wang, J.S. Shen, Z.H. An, Y. Yang, L. Zeng, X.C. Wei, G.S. Li, X. Zhu, T. Lan, and H.B. Wang, *Optical Layout and mechanical structure of polarimeter-interferometer system for EAST tokamak*, Rev. of Sci. Instr. **85**, 11D409 (2014)
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Conclusions: Scenarios and Control Collaboration Has Been Very Successful

- **Scenario understanding is advancing through transfer from US devices to EAST/KSTAR, enabled by simulations and analysis**
- **Control science understanding has advanced through EAST/KSTAR algorithm development and experiments**
- **Diagnostics development on EAST are enabling measurements critical to scenarios and control physics**
- **Actuator modeling is contributing to improved utilization on EAST and high-fidelity model-based control development for both EAST and KSTAR**
- **Simulations of advanced scenarios are accelerating EAST and KSTAR research programs**
- **Remote collaboration research and development is on track to enable access by US scientists to entire EAST 3rd shift**